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DETERMINATION OF DOPPLER (LASER) GEODESIC NETWORK
LONGITUDE ZERO POINT DIFFERENCES

by

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ABSTRACT

Longitudes associated with Doppler (laser) positioning measured by survey stations only possess relative significance. In order to obtain absolute longitudes, it is necessary to determine orientations of Doppler (laser) network longitude zero points in BIH-CIO systems. This article discusses making use of small numbers of optical observations to determine longitude zero point difference questions, giving dynamic determination and geometrical determination methods. In conjunction with this, discussions are made of their.optimum observation conditions.

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I. INTRODUCTION

As is widely known, in Doppler (laser) dynamic geodesy, due to partial derivatives associated with observation amounts $\dot{\rho}$, and λ with regard to observation station longitude and orbital ascending node longitude Ω, one has the relationship below:

$$\frac{\partial(\dot{\rho}, \Delta\rho, \rho)}{\partial\lambda} = -\frac{\partial(\dot{\rho}, \Delta\rho, \rho)}{\partial\Omega}, \qquad (1)$$

The normal equations obtained are not fully ordered. Problems have infinitely numerous multiple element solutions.

In cases where there are no optical observations, in empirical measurements, the longitude λo associated with a certain observation station (designated the zero point station) is usually given in order to resolve this difficulty. However, longitudes we obtain in this way are not then "absolute longitudes" measured from BIH zero meridian lines. They are, by contrast, "relative longitudes" measured from another measurement start point (a place λo to the west of the zero point station). The difference between observation station relative longitudes and absolute longitudes we designate as "longitude zero point difference".

Obviously, in order to obtain absolute longitudes, following Doppler (laser) dynamic geodetic measurements, it is still necessary to determine "longitude zero point difference".

In satellite earth surveying outside of China, longitude zero point problems are solved by the use of methods associated with combinations of optical observations [1]. This type of method requires having a considerable number of optical observations which it is possible to independently verify precise orbits for or having a certain number of Doppler (laser) optical satellite observations. Due to Doppler (laser) satellites being very dark and weak, if one wishes to acquire these materials, it is very difficult. This article discusses how to make use of relatively scarce optical observations in order to determine longitude zero point difference questions associated with Doppler (laser) dynamic geodetic networks. In conjunction with this, discussions are made of their optimum observation conditions.

II. DYNAMIC METHODS TO DETERMINE LONGITUDE ZERO POINT DIFFERENCES

From now on, we assume that use has already been made of Doppler (laser) observations and dynamic methods to acquire measurements for observation station coordinates associated with a certain geodetic network (longitude zero point differences exist in longitudes) as well as orbit radicals associated with segmental arcs of various satellites. In this section, we assume that certain stations in this network also obtain a few Doppler

(laser) optical satellite observations. However, the number is very small. It is not possible to make direct combinations /148 with Doppler (laser) observations in simple ways during dynamic solutions--solving for absolute longitudes of observation stations. Below, we discuss how, in this type of situation, to determine questions of longitude zero point differences.

1. Determination Principles

The basic principles of dynamic methods to determine longitude zero point differences are the same as dynamic geodetic surveys. It is simply that, now, relative measurement station locations as well as satellite orbits are already measured by Doppler (laser) observations. There is only one longitude difference point $\Delta\lambda$ which is an unknown quantity. However, when setting out condition equations, it is necessary to pay attention to whether or not orbits of various satellites are determined in cases with given zero point station longitudes. As a result, satellite ascending node longitudes Ω also include longitude zero point differences. Because of this, condition equations should be

$$\left(\frac{\partial(\alpha,\delta)}{\partial\lambda}+\frac{\partial(\alpha,\delta)}{\partial\Omega}\right)\Delta\lambda=(\alpha_0-\alpha_c,\ \delta_0-\delta_c), \tag{2}$$

but are not

$$\frac{\partial(\alpha,\delta)}{\partial\lambda}\Delta\lambda=(\alpha_0-\alpha_c,\ \delta_0-\delta_c). \tag{3}$$

Here, (α,δ) is satellite right ascension and declination. Subscripts "O" and "c" stand for observation values and calculated values associated with observation station coordinates and orbit radical calculations obtained during Doppler (laser) dynamic geodetic surveying.

It should be pointed out that α,δ measured making use of equation (3) and measured with equation (2) are always opposite in sign. We are not able to use iterative approximation methods in order to solve for true values of $\Delta\lambda$. It is not difficult to demonstrate that:

$$\frac{\partial\alpha}{\partial\lambda}+\frac{\partial\alpha}{\partial\Omega}=1, \tag{4}$$

$$\frac{\partial\delta}{\partial\lambda}+\frac{\partial\delta}{\partial\Omega}=0. \tag{5}$$

These are two extremely important relationships. From these, conditions equations associated with determinations of longitude zero point differences then become very simple:

$$\Delta\lambda=\alpha_0-\alpha_c. \tag{6}$$

Obviously, at this time, dynamic solutions and multiple point mean differences are all very simple. The above are the basic principles associated with dynamic methods of determining longitude zero point differences.

2. Elimination of Errors Along Tracks

As is shown in Fig.1, AB is the satellite vision locus. CD is the calculated locus in cases where there are longitude zero point differences. Assuming that the actual satellite position at time t is Po, when there are errors along loci, the observation point is P. In the same way, the correctly calculated position of the satellite at instant t is P'o . Yet,

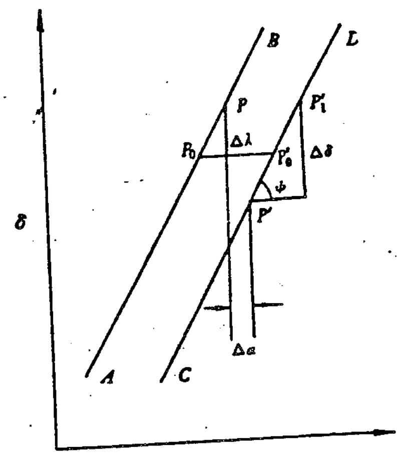

Fig.1 Influences of Errors Along Loci With Regard to the Determination of Longitude Zero Point Differences

when there are errors along loci, it is P'. From equation (6), one knows that the right ascension difference between Po and P'o is Δλ. However, what we actually get is the right ascension difference of Po and P', ΔÁ. As a result, it is possible to see that the influences of differences along loci on determinations of ΔÁ are very great. We must study methods of eliminating this. The key to eliminating differences along loci is equation (5). From equation (5), one knows that Δλ certainly does not give rise to errors in Š directions. As a result, in Fig.1, AB and CD are parallel. Moreover, PoP'o and Á axes are parallel. To say it the other way around, Š direction errors are not given rise to by Δλ. When determining longitude zero point differences, they should be eliminated. As far as eliminating Š errors is concerned, it is also the elimination of differences along loci.

Moreover, eliminating Š errors is convenient. It only requires finding a t′ around t, making Šc and Šo equal to each other, and that will do it. Looking at the Fig.'s, that is, finding a point P′1 on CD, make Šc associated with P′1 and Šo associated with P equal to each other. After that, make use of Áo associated with point P, subtracting Ác associated with P′1, to obtain $\Delta\lambda$. /149

If one does this rigorously, calculations are also certainly not difficult. However, if ΔÁ and ΔŠ associated with P and P′ are certainly not very large, as far as $\Delta\lambda$ is concerned, it is possible to make use of the equations below to do calculations:

$$\begin{aligned}\Delta\lambda &= \Delta\alpha - \operatorname{ctg}\psi\Delta\delta/\cos\delta \\ &= \frac{1}{\cos\delta\sin\psi}(\Delta\alpha\cos\delta\sin\psi - \cos\psi\Delta\delta),\end{aligned} \tag{7}$$

In this, ψ is the included angle between satellite visual loci and Á directions. The algorithm is as follows [2]:

$$\cos\psi = \boldsymbol{a}\cdot\boldsymbol{G}, \quad \sin\psi = -\boldsymbol{a}\cdot\boldsymbol{g}. \tag{8}$$

Here,

$$\boldsymbol{a} = \begin{pmatrix} -\sin\alpha \\ \cos\alpha \\ 0 \end{pmatrix}, \quad \boldsymbol{g} = \frac{\boldsymbol{\rho}}{\rho}\times\dot{\boldsymbol{\rho}} \Big/ \left|\frac{\boldsymbol{\rho}}{\rho}\times\dot{\boldsymbol{\rho}}\right|, \quad \boldsymbol{G} = \boldsymbol{g}\times\frac{\boldsymbol{\rho}}{\rho}, \tag{9}$$

In the equations, ρ and $\dot{\boldsymbol{\rho}}$ are position vectors and velocity vectors of satellites relative to measurement stations. The algorithm is omitted.

To summarize what was discussed above--in order to eliminate the influences of differences along loci--as far as condition equations associated with $\Delta\lambda$ are concerned, it is possible to make use of equation (7). Test calculations clearly show that doing this is successful.

3. Error Estimation, Weighting, and Optimum Conditions

Assuming that ÁocosŠ, Šo joint observation difference matrix is Qo, it is possible to do calculations to get it from negative treatments. ÁccosŠ, Šc joint difference matrix is Qc. It is possible to obtain it from orbit radical and station coordinate joint difference matrix propagation. Then, as far as $\Delta\lambda$ variance is concerned, from equation (7), one conveniently knows it to be:

$$\sigma^2_{\Delta\lambda} = \frac{1}{\sin^2\psi \cos^2\delta}\left[(\sin\psi, -\cos\psi)Q_o\begin{pmatrix}\sin\psi \\ -\cos\psi\end{pmatrix} + (\sin\psi, -\cos\psi)Q_c\begin{pmatrix}\sin\psi \\ -\cos\psi\end{pmatrix}\right], \tag{10}$$

Because of this, at times of multiple point mean difference, with regard to equation (7) weighting, it is possible to use

$$W = \frac{1}{\sigma^2_{\Delta\lambda}}. \tag{11}$$

From this, it is possible to see that optimum conditions associated with observation are 1 = 90½, Š = O. That is equivalent to observations from a satellite with a relatively large angle of inclination on the celestial equator. Besides that, because we make use of equation (7) to eliminate differences along loci, equation (10) quantities in brackets are variances associated with directions perpendicular to loci. Therefore,

$$\sigma^2_{\Delta\lambda} = \frac{1}{\sin^2\psi \cos^2\delta}[\sigma^2_{\perp o} + \sigma^2_{\perp c}]. \tag{12}$$

If we use Íperpendicular o = Íperpendicular c = O''.5 in order to make estimates, in cases where attention is paid to optimum observation conditions (sin2 ψ cos2 Š > 0.75), the precision of $\Delta\lambda$ obtained by an observation is, then, approximately 1''. As far as 100 observations distributed in 20 segmental arcs are concerned, the precisions of $\Delta\lambda$ are, by contrast, approximately 0.''16, that is 5 meters

III. GEOMETRIC DETERMINATION METHODS FOR LONGITUDE ZERO POINT DIFFERENCES

In this section, we assume that a certain two observation stations in a Doppler (laser) dynamic geodetic network carry out synchronous observations, in order to discuss problems associated with determinations of $\Delta\lambda$.

1. Basic Principles

From the synchronous plane determined by synchronous observations rA and rB obtained from two stations A and B, it is possible to conveniently convert into BIH-CIO systems. Moreover, making use of observation station coordinates obtained using Doppler (laser) observations--if longitude zero point differences are included--their hypotenuse directions are then not included within this synchronous plane. On the basis of this difference, it is then possible to solve for $\Delta\lambda$. This is nothing else than the basic principle associated with geometrical methods to determine longitude zero point differences.

Assume that directions associated with rA and rB after transfer to BIH-CIO systems are

$$l_A = \begin{pmatrix} \cos\delta_A & \cos\alpha_A \\ \cos\delta_A & \sin\alpha_A \\ & \sin\delta_A \end{pmatrix}, \tag{13}$$

$$l_B = \begin{pmatrix} \cos\delta_B & \cos\alpha_B \\ \cos\delta_B & \sin\alpha_B \\ & \sin\delta_B \end{pmatrix}. \tag{14}$$

The hypotenuse direction associated with the two points AB is

$$l = S\begin{pmatrix} \cos\varphi' & \cos\lambda \\ \cos\varphi' & \sin\lambda \\ & \sin\varphi' \end{pmatrix} = \begin{pmatrix} \Delta X \\ \Delta Y \\ \Delta Z \end{pmatrix}, \tag{15}$$

Here, (ÁA,ŠA), (ÁB,ŠB), and (λ ,Ú′) are, respectively, spherical coordinates associated with lA, lB, and l. S is hypotenuse length.

Making the definition

$$n = \frac{l_A \times l_B}{|l_A \times l_B|} = \begin{pmatrix} A \\ B \\ C \end{pmatrix}, \tag{16}$$

the coplanar condition is then

$$n \cdot l = 0. \tag{17}$$

Due to the existence of longitude zero point differences, one then has

$$n \cdot l_0 + n \cdot \Delta l = 0. \tag{18}$$

In this, lo is a measurement station coordinate calculation determined by Doppler (laser). Δl is the hypotenuse direction difference given rise to by longitude zero point differences. Obviously,

$$\Delta l = \begin{pmatrix} -\Delta Y \\ \Delta X \\ 0 \end{pmatrix} \Delta \lambda. \tag{19}$$

Because of this, the condition equation associated with determining Δλ is

$$(A\Delta Y - B\Delta X)\Delta\lambda = A\Delta X + B\Delta Y + C\Delta Z. \tag{20}$$

This is the basic equation associated with determining .Δλ. It is very simple. /151

2. Error Estimates and Weighting

Assume that the joint difference matrix associated with synchronous observations is

$$R = \begin{pmatrix} \sigma^2_{\alpha_A \cos\delta_A} & \sigma_{\alpha_A\delta_A} & 0 & 0 \\ \sigma_{\alpha_A\delta_A} & \sigma^2_{\delta_A} & 0 & 0 \\ 0 & 0 & \sigma^2_{\alpha_B \cos\delta_B} & \sigma_{\alpha_B\delta_B} \\ 0 & 0 & \sigma_{\alpha_B\delta_B} & \sigma^2_{\delta_B} \end{pmatrix}, \tag{21}$$

On the basis of error propagation principles, the equation to determine $\Delta\lambda$ is

$$\sigma^2_{\Delta\lambda} = P^{\tau} R P, \tag{22}$$

In this, P^{τ} expresses P transpositions, being

$$P^{\tau} = \left(\frac{\partial\lambda}{\partial\alpha_A} \frac{1}{\cos\delta_A}, \frac{\partial\lambda}{\partial\delta_A}, \frac{\partial\lambda}{\partial\delta_B} \frac{1}{\cos\delta_B}, \frac{\partial\lambda}{\partial\delta_B} \right). \tag{23}$$

It is not difficult to deduce [3]

$$\begin{aligned} \frac{\partial\lambda}{\partial\alpha_A} \frac{1}{\cos\delta_A} &= -\frac{b_1}{b_3}, & \frac{\partial\lambda}{\partial\delta_A} &= -\frac{a_1}{b_3}, \\ \frac{\partial\lambda}{\partial\alpha_B} \frac{1}{\cos\delta_B} &= -\frac{b_2}{b_3}, & \frac{\partial\lambda}{\partial\delta_B} &= -\frac{a_2}{b_3}. \end{aligned} \tag{24}$$

In this,

$$\begin{aligned} a_1 &= \rho_A^2 \rho_B \cos\delta_B \sin(\alpha_A - \alpha_B), \\ a_2 &= \rho_B^2 \rho_A \cos\delta_A \sin(\alpha_B - \alpha_A), \\ b_1 &= \rho_A^2 \rho_B [\sin\delta_B \cos\delta_A - \sin\delta_A \cos\delta_B \cos(\alpha_A - \alpha_B)], \\ b_2 &= \rho_A \rho_B^2 [\sin\delta_A \cos\delta_B - \sin\delta_B \cos\delta_A \cos(\alpha_A - \alpha_B)], \\ b_3 &= (\boldsymbol{k} \times \boldsymbol{l}) \cdot (\rho_A \boldsymbol{l}_A \times \rho_B \boldsymbol{l}_B), \\ \boldsymbol{k} &= \begin{pmatrix} 0 \\ 0 \\ 1 \end{pmatrix}. \end{aligned} \tag{25}$$

Here, ρA and ρB are the distances from satellites to measurement stations A and B. With regard to any synchronous observations associated with an already known R, it is then possible to calculate $\sigma^2_{\Delta\lambda}$. These are $\Delta\lambda$ variance estimates. When there are multiple point mean differences, equation (20) is capable of using $W = \frac{1}{\sigma^2_{\Delta\lambda}}$ in order to add weighting.

3. Optimum Observation Conditions

On the basis of $\sigma^2_{\Delta\lambda}$ associated with synchronous observations, it is possible to discuss optimum observation conditions associated with geometric methods of determining longitude zero point differences. It is simply that we must set up a way of predicting beforehand joint difference matrices R associated with an observation.

(1). Estimations of Observation Joint Difference Matrices

Assuming that satellite inclination angles are i, ground heights are H, and, in conjunction with that, assuming that

satellites are in circular orbits, then, with regard to observation joint difference matrix $Q_{\alpha\delta}$ with respect to (λs,Ús) for observation station (λ,Ú) and subsatellite point (λs,Ús), it is possible to make use of the formula below to do calculations:

$$Q_{\alpha\delta}=\begin{pmatrix}\cos\phi & -\sin\phi\\ \sin\phi & \cos\phi\end{pmatrix}\begin{pmatrix}\sigma^2_{\text{Ⅱ}} & 0\\ 0 & \sigma^2_{\perp}\end{pmatrix}\begin{pmatrix}\cos\phi & \sin\phi\\ -\sin\phi & \cos\phi\end{pmatrix}, \tag{26}$$

In this, ϕ is defined the same as in equation (8). It is simply that satellite orbit ascending node longitudes must make use of subsatellite point latitudes and longitudes to deduce backwards, and that is all. The algorithm is

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$$\Omega=\lambda_s-L,$$

$$L=\mathrm{tg}^{-1}\left[\frac{\cos i\ \sin u}{\cos u}\right], \tag{27}$$

$$\sin u=\frac{\sin\varphi_s}{\sin i},$$

Ascending sections are positive. Falling sections are negative. If one has õ, calculating rs, $\dot{r}$, ρ, $\dot{\rho}$ is simple. Then, making use of the two equations (8) and (9), it is possible to obtain ϕ.

When estimating $Q_{\alpha\delta}$, observation differences along loci Íalong associated with observation stations as well as observation differences perpendicular to loci Íperpendicular are given. Based on experience with actual measurements, Íalong and Íperpendicular are basically constants for a single instrument. During estimates of $Q_{\alpha\delta}$, giving them is even more reasonable than directly giving $Q_{\alpha\delta}$. As a result, when we are discussing optimum observation conditions in this instance, option is made for the use of this method to predict R.

To summarize, after we gave Íalong and Íperpendicular for two stations--under the assumed conditions described above--it is then possible to estimate R associated with any single subsatellite point, thereby calculating out $\sigma^2_{\Delta\lambda}$ associated with the synchronous observations in question. It is then possible to discuss optimum observation conditions associated with geometrical methods.

(2). A Few Points of Discussion Associated with Optimum Observation Conditions

In order to discuss optimum observation conditions, we made simulation calculations. In situations with given λ_A, φ_A, λ_B, φ_B, i = 90½, Íalong = 1'', Íperpendicular = 0''.5, H as well as ascending and descending section signs, $\sigma^2_{\Delta\lambda}$ was calculated.

A few preliminary conclusions were arrived at. Discussion is currently as follows:

a) The lower satellites are the better.

Calculations were done of three types of cases: $\varphi_A = \varphi_B = 30°$, $S = 2000\ KM$, $H = 4000, 2000, 1000$ kilometers. Table 1 was obtained. It is not difficult for us to see that the lower H is the better.

Table 1

$\sigma^2_{\Delta 1}$ / H	最佳值 (1)	4°×6° 最佳区平均值 (2)	8°×12° 最佳区平均值 (2)
4000	1.47	1.50	1.57
2000	0.46	0.50	0.57
1000	0.17	0.20	0.24

KEY: (1) Optimum Value (2) Optimum Zone Average Value

b) In cases where S and H are the same, the higher observation station latitudes are, the more advantageous it is. Calculations were done of three types of cases: $\varphi_A = \varphi_B = 0°, 30°, 60°$, $S = H = 2000$ kilometers. Table 2 was obtained. It is not difficult to see that the higher Ú is, the more advantageous it is.

Table 2

$\sigma^2_{\Delta 1}$ / φ	最佳值 (1)	4°×6° 最佳区平均值 (2)	8°×12° 最佳区平均值 (2)
0	1.15	1.30	1.42
30°	0.46	0.50	0.57
60°	0.38	0.42	0.50

KEY: (1) Optimum Value (2) Optimum Zone Average Value

c) In cases where S, H, and average latitudes are the same, two stations distributed on a ring of the same latitude is advantageous. During calculations, S = H = 2000 kilometers, and Ůaverage = 30½. Calculations were done of four types of cases where azimuth angles associated with station B relative to /153 station A were A = 0½, 30½, 60½, and 90½. Table 3 was obtained. From this, it is possible to see that two stations distributed on the same latitude ring (A = 90½) is relatively advantageous.

Table 3

$\sigma^2_{\Delta l}$ / A	最佳值 (1)	4°×6° 最佳区平均值 (2)	8°×12° 最佳区平均值 (2)
0	0.50	0.58	0.73
30°	0.49	0.54	0.63
60°	0.47	0.51	0.62
90°	0.46	0.50	0.57

KEY: (1) Optimum Value (2) Optimum Zone Average Value

d) In cases where H/S are the same, the farther the distance is between two stations, the more advantageous it is. Calculations were done of three cases where $H/S = 2, \varphi_A = \varphi_B = 30°$, $S = 1000, 2000, 3000$ kilometers. Table 4 is obtained. From this, it is possible to see that, the larger S is, the more advantageous it is.

Table 4

$\sigma^2_{\Delta\lambda}$ / S	(1) 最佳值	4°×6° 最佳区平均值 (2)	8°×12° 最佳区平均值 (2)
1000	1.71	1.79	1.97
2000	1.47	1.50	1.57
3000	1.30	1.34	1.42

KEY: (1) Optimum Value (2) Optimum Zone Average Value

e) Optimum Zone Distribution Status

Looking at situations associated with calculations, as far as subsatellite points that are not the same are concerned, $\sigma^2_{\Delta\lambda}$ is very greatly different. With regard to optimum zone distributions, although there are differences with b3 = max regions, they are still in the vicinity. We can approximate the use of b3 = max conditions in order to seek out optimum subsatellite distributions. However, with a view to accuracy, it is best to use the methods above to make a concrete calculation of ($i = 90°$) values associated with various subsatellite points, thereby searching out optimum zones. Doing things this way is a great advantage with respect to organizing observations. In order to elucidate this question, Fig.2 gives a distribution chart associated with $\sigma^2_{\Delta\lambda}$ using 3500 kilometer round orbit satellites (i = 90½). It is not difficult to see that looking for subsatellite point optimum zones is very important. The reason is that, as far as an optimum zone observation is concerned, it is possible to arrive at a few to several tens of observations associated with other areas. There are a number of observations associated with the worst zones (b3 = 0) which are almost useless with regard to determining longitude zero point differences.

Besides this, we also discovered the phenomenon that, when

subsatellite point loci and hypotenuse directions are in agreement, $\sigma^2_{\Delta\lambda}$ is optimum. However, due to the fact that, if one wishes to fully explain this point, it is necessary to have very exhaustive calculations, we only calculated four types of A (A=90½, 60½, 30½, 0½) and three types of i (i=90½, 60½, 45½) cases of ascent and descent, agreeing with this conclusion.

4. Precision Estimates

If we pay attention to the most advantageous observation conditions, $\sigma^2_{\Delta\lambda}$ = 2 observations are not difficult to obtain. As a result, as far as 100 pairs of synchronous observations are concerned, if $\Delta\lambda$ determination precisions will be better than 0.''14, it is possible to match the precision of dynamic methods associated with 100 Doppler (laser) optical satellite observations. Here, we must also point out that this 100 pairs of synchronous observations certainly do not require two observation stations which are the same in order to obtain them. Observed measurements associated with any two observation stations will do. It is only necessary that the total number reaches 100 pairs, and that will do it. From this, it can be seen that geometrical measurement requirements for observed measurements are also not high. /154

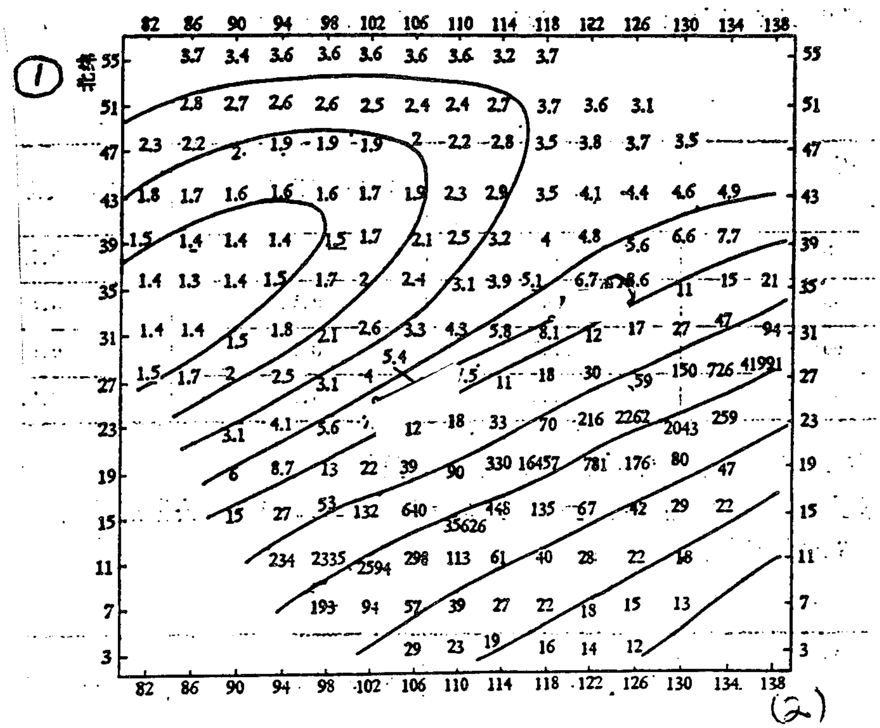

Fig.2 Distribution Chart for Nanjing-Kunming Synchronous Observation $\sigma^2_{\Delta\lambda}$ (i = 90½, H = 3500 kilometers)

KEY: (1) North Latitude (2) East Longitude

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